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WAYNE KERR

AUTOBALANCE PRECISION BRIDGE

B331

Operating Instructions

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B331

Operating Instructions

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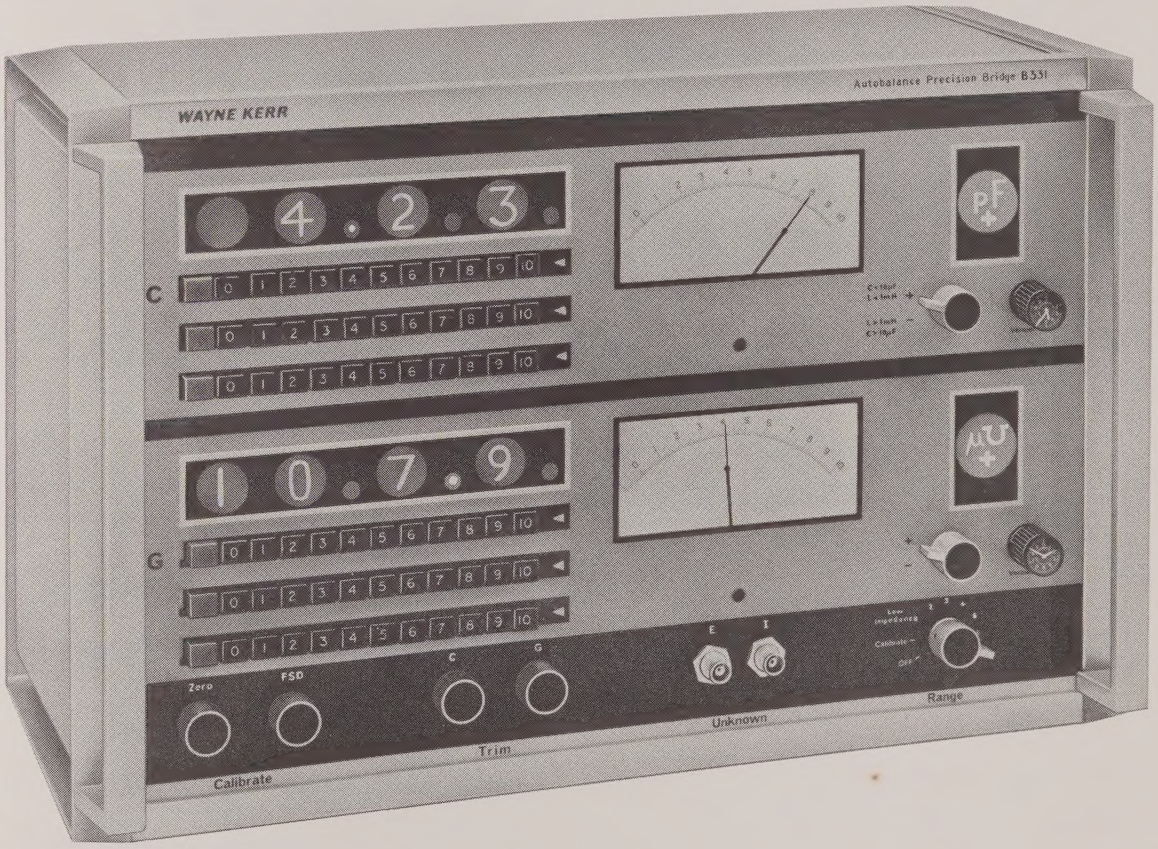
WAYNE KERR
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C
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Calibrate
E
I
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INTRODUCTION

The Autobalance Precision Bridge B331 is an instrument for the audio frequency measurement of admittance in all four quadrants of the complex plane. The instrument combines speed and simplicity of operation with 0.01% accuracy.

The capacitance and conductance of the component under test are displayed initially on the two meters. Six push-button decades, three for capacitance and three for conductance, are operated in succession, the sensitivity of the meters being increased as each pair of decades is operated. Each decade is associated with a neon indicator tube which displays the selected number. The Range switch is associated with another illuminated display that shows the units and multiplying factor appropriate to the range in use. Thus it is virtually impossible to make an incorrect reading of the result.

At each stage in the sequence of operation of the decades, an illuminated arrowhead indicator points to the next decade to be operated until the full accuracy of 0.01% is attained. The decimal point is always shown in the correct position in relation to the multiplying factor, and so the process can be ended at any stage depending on the accuracy required. However, when the final decades are operated, any multiplication factor applicable in the earlier stages of the measurement is automatically applied, the decimal point being moved if necessary, and the read-out is then direct in units.

Two calibrated vernier potentiometers are provided, by means of which the meters can be partly or wholly backed off. These controls can be set and read to three significant figures so that, by using them to back off the meters to zero, enhanced discrimination can be obtained.

An important feature of the B331 is its ability to measure low values of impedance with but little regard to the impedance of the measurement connecting leads. The instrument incorporates a special circuit known as the 'lead eliminator' because it greatly reduces the errors that would otherwise result from the use of long connecting leads.

The continuous self-balancing of the bridge, combined with its high order of accuracy and sensitivity, makes the instrument particularly suitable for the observation and measurement of small temperature coefficients and similar drift measurements.

A pair of sockets behind the left-hand door allows the connection of an external standard to back windings; various uses of this facility are explained in the text. The voltages equivalent to that part of the C and G values of the test component given by the meters are available at sockets - also behind the left-hand door - for the operation of external recorders or digital voltmeters.

Although the instrument standards are of capacitance and conductance, resistance and inductance can also be measured, reciprocal tables being provided at the end of the book. To simplify the derivation of those values which are frequency-dependent, the oscillator is adjusted to 1591.55Hz (at which frequency $\omega = 10^4$).

Instruments are available (to special order) for operation at a frequency of 1000Hz but with these, the measurement of inductance requires a calculation instead of a simple reference to reciprocal tables. Also, since 1000Hz instruments use the same reference standards as are used in 1592Hz instruments, there are two small regions in the measurement range that require a modified operating procedure. These occur from 10 - 25μF and 1 - 2.5mH.

Both instruments have provision for operation with an external source and detector; this is necessary if operation is required at any frequency other than that given by the internal source. However, under these conditions, the autobalance feature does not operate, the bridge being manually balanced by means of the decade switches and vernier controls.

OPERATING INSTRUCTIONS

Connection to Power Supply

Connect a 3-pin plug to the power lead supplied; red to live, black to neutral, green to ground.

Open the right-hand door and check that the power adjustment plug is set to the position appropriate to the voltage of the supply to be used. Feed the supply connector through the aperture in the door and insert it in the supply socket. Close the door. The power supply fuse (250mA rating) is located behind this door.

Open the left-hand door and check that the switch 'External' is set to its maximum counter-clockwise position. Close the door.

Since the instrument is transistorized, it is ready for use within approximately twenty seconds of switching on.

Connection of Component under Test

The lead eliminator circuit operates on Ranges 1, 2, 3 and 4 to reduce errors normally associated with the use of long connecting leads, but it is essential that the component under test is connected to the leads in the correct manner (see Fig. 1). The unknown sockets on the B351 are double-screened and so each measurement cable comprises three leads, one being the normal E or I lead, the second is the neutral lead and the third is the connection to the lead eliminator circuit. The cables are terminated at one end with a special B. N. C. connector to mate with those on the front panel.

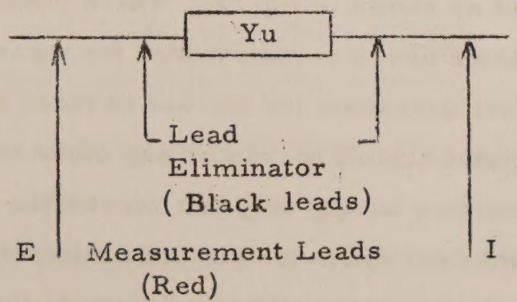

Fig. 1
Lead Eliminator
Connections

The instrument is supplied with two pairs of measurement leads; one pair is terminated with Kelvin clips at the test component end, the other pair having flying leads fitted with crocodile clips. In both cases the cables are terminated at the instrument end with BNC triaxial connectors. A special terminal block incorporating scissor-type connectors is available as an optional extra.

The Kelvin clips have a small plastic insert that can be slid between the two connectors. The purpose of this is to isolate the lead eliminator connection on Ranges 5-8. These leads should be used whenever possible since they automatically make the correct connections to the lead eliminator. The leads are used as shown in fig. 2A.

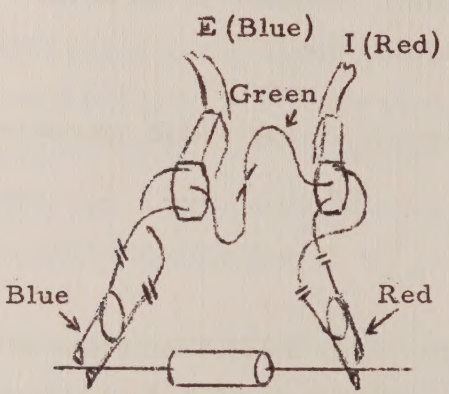

Fig. 2A

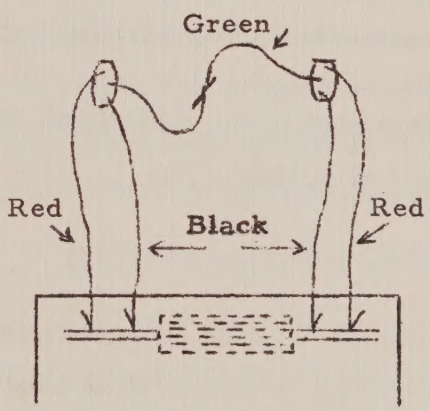

Fig. 2B

Fig. 2. Connection of Test Component

In some cases, the use of the Kelvin clips is impracticable or unadvisable and the crocodile clip leads must be used instead. These should be connected to the test component as shown in fig. 2B. These leads have a specially low impedance and their use is recommended for measurements at the low end of Range 2. Other occasions for the use of these leads are, for example, measurements on printed circuit boards or any other case where the unknown is in the form of a surface having only one accessible side. In other cases, there may not be sufficient space for the connection of a Kelvin clip, then provided that the lead eliminator clip is adjacent to the unknown, the measurement lead can be some distance away - even having switch contacts

between them.

In both pairs of cables, one is colour-coded blue and the other red at the B. N. C. connector. Always connect the blue coded cable to the Unknown E socket, and the red coded cable to the Unknown I socket. In the cables fitted with crocodile clips the leads are colour-coded red, black and green by means of coloured marker sleeves. The red coded lead is the signal, or measurement lead, the black coded lead is the lead eliminator connection and the green coded lead is neutral.

Trimming and Calibration

1. Connect the appropriate measurement cables to the Unknown E and I sockets. Connect together the green leads from each cable as shown in fig. 2. If the crocodile clip cables are being used, connect the red coded lead in each cable to the black coded lead in the same cable. If the Kelvin clip cables are being used, ensure that the plastic insert in each clip is slid back. Do NOT connect the test component at this stage.

NOTE: This operation does not apply when the Low Impedance Range 1 is to be used; see the Section 'Low Impedance Measurements'.

2. Press the 0 button on the lowest G decade and ensure that on all other decades the red button is pressed.

3. Set:
   (a) the Range switch to Calibrate
   (b) the Vernier C and Vernier G controls to zero (maximum counter-clockwise)
   (c) both polarity switches to +.

4. Adjust:
   (a) Trim C for 0 indication on the C meter
   (b) Trim G for 0 indication on the G meter

5. Press button 1 on the lowest G decade.

6. Adjust:
   (a) Calibrate F. S. D. control for full scale deflection on the G meter
   (b) Calibrate Zero control for 0 indication on the C meter.

7. Press the red reset button on the lowest G decade.

Normal Measurements

The following operations cover normal two-terminal measurements at 1592Hz. Low Impedance (Range 1) measurements and three- or four-terminal measurements are dealt with under their respective headings. For measurement at other frequencies, see 'External Source and Detector'.

The basic procedure for normal measurements is the same regardless of the nature of the component under test. When the measurement is completed, interpret the displayed result as described in the next section. The user is advised to read through this and the next section before commencing to use the bridge.

1. Set the Range switch to 2 and connect the test component as shown in fig. 2A or 2B as appropriate.

2. Observe the meter indications. If both are between 0 and 1, change to Range 3 and, if necessary, to higher ranges until the larger of the two meter indications is between 1 and 10. If greater than 10, refer to 'Low Impedance Measurements'. If, at this stage, either of the two meter indications is negative, change the appropriate polarity switch to '-'.

3. If an indication to two significant figures is satisfactory, no further operations are necessary. Multiply the C and G meter indications by the appropriate factors given in the illuminated displays to the right of the meters and refer to the next section - Interpretation of Results. However, if greater accuracy is required, proceed as follows.

4. Notice that the arrowhead to the right of the top C decade is illuminated. This, and similar indicators for the other decades, shows the next decade that must be operated in the progression towards maximum sensitivity and accuracy. Press the decade button corresponding to the first figure of the C meter indication (press the 0 button if the deflection is less than 1).

5. When the C decade button is pressed, the C meter indication (if any) falls, but the associated display tube is not immediately illuminated; this prevents the making of a false reading. Notice that the pointer to the right of the top G decade is now illuminated.

6. Press the top G decade button corresponding to the first figure of the G meter indication (0 for an indication less than 1). This will have the following results:

(a) The C and G display tubes associated with the top decades become illuminated.

(b) The meters now indicate the second and third significant figures.

(c) The pointer to the right of the centre C decade is illuminated.

At this stage, although the full accuracy is not attained, the display is a three-figure indication of the C and G values of the component under test, requiring only the application of the multiplying factors for the range in use.

7. By using successive C and G decades in the same manner and always in the order indicated by the illuminated pointers, the display can be increased up to a maximum of five significant figures (or six significant figures at range maximum), the last two of which are always given by the appropriate meter indication; the accuracy is then 0.01%. Operation of the third C and G decades changes the associated multiplication factor to unity and simultaneously moves the decimal point to its correct position in the display. Thus the operation of the multiplication factor is performed automatically.

8. When the required values have been noted, press all the red reset buttons in readiness for the next measurement. Disconnect the test component.

Special Case of Capacitance between 10 - 25μF and Inductance between 1 - 2.5mH on Instruments having an Internal Source Frequency of 1000Hz

The achievement of the very low impedance range (0 - 10mΩ) leaves two small gaps in the range of normal measurements when the operating frequency is 1000Hz; these occur between 10 - 25μF and 1 - 2.5mH. However, components whose value is between these limits can be measured by making use of the Offset Winding. The terminals giving access to this are located behind the left-hand door and are marked E_{10} and I_{-12}. The ratio of the transformer windings is such that for each micro-farad that is to be backed off (on Range 2), one nano-farad (1000pF) must be connected between the E_{10} and I_{-12} terminals.

As an example, assume that a capacitance of value 12μF is to be measured. Assume also that the amount to be backed off is 10μF. A capacitor of value 10nF (0.01μF) must be connected between the E_{10} and I_{-12} terminals. The measurement then proceeds as though the value of the component were 2μF. Note that the amount to be backed off can be any value that leaves the portion to be measured within the range of normal measurements. It will, perhaps, be decided by the value of components available for backing off. For greatest accuracy, the component used for this purpose should itself be measured as under normal measurements. Having connected the backing-off component, the measurement is performed as already described, the displayed result then being added to the amount backed off.

Thus, the procedure for establishing the value of the Unknown is as follows:

1. Having connected the backing-off capacitor and the Unknown, note the Bridge indication directly in μF.

2. Remove the backing-off capacitor from the E_{10} and I_{-12} terminals and then measure its value on the Bridge by the normal procedure. Multiply the Bridge indication by 1000 (1nF on the backwinding equals 1μF in the Unknown arm).

3. The required value is the sum of the two values thus obtained.

Interpretation of Results

The foregoing procedure applies basically to the measurement of any normal component (i. e., one whose value is within the scope of Ranges 2-8 inclusive).

If the component under test is a capacitor, the value of C is read directly from the display. The displayed value of G is the parallel conductance of the component. To interpret this value in terms of parallel resistance, take the reciprocal of the value for G (refer to the table of reciprocals at the end of this book), and the reciprocal of the displayed G units, i. e.,

$$\frac{1}{\mho} = \Omega\,; \qquad \frac{1}{m\mho} = k\Omega\,; \qquad \frac{1}{\mu\mho} = M\Omega$$

In nearly all cases the G polarity switch will be set to '+' for a positive indication on the G meter. However, some networks have a negative

resistance characteristic in certain circumstances; in such cases, the G polarity switch may require setting to '-'.

If the test component is a resistor having a small reactance, the C meter indication will probably be less than 1 initially, in which case the 0 button on the first C decade should be pressed. However, a wire-wound resistor may have an inductive reactance and this will require the C polarity switch to be set to '-'. In this case it will be necessary to take the reciprocal of both displays since

$$R = \frac{1}{G} \qquad \text{and} \qquad L = \frac{1}{\omega^2 C} \text{ where } \omega^2 = 10^8 \text{ at 1592Hz.}$$

If it is desired to express the reactance term in the series form, conversion formulae (parallel to series) are given on page 21.

If the test component is an inductor, the C polarity switch can be set to '-' before commencing the measurement procedure. To determine the value of the inductance, use the expression given above. Note that, for accurate results, the value of the self-capacitance (if known) of the inductor should be added numerically to the Bridge C reading (making the reading more negative) before using the above expression. The value of most inductors is modified by their proximity to metal objects and so a free air-space round the component should be ensured.

Low Impedance Measurements

The procedure for the measurement of low impedances (as covered by Range 1) is as follows.

1. Leave the green lead of each measurement cable unconnected (it can be conveniently clipped back on the main cable, see fig. 3). If the crocodile clip cables are being used the remaining four leads - two red and two black - should be connected together as shown in fig. 3. In the case of the Kelvin clip cables, the clips should be connected together by attaching them close together on a short length of copper rod.

2. Calibrate the instrument using the procedure given in operations 3 - 7 inclusive on page 9.

3. Set the Range switch to 1 (or Low Impedance).

4. Press the 0 button on the lowest G decade; ensure that the red reset button is pressed on all other decades.

5. Check the adjustment of the Trim C and Trim G controls for 0 indication on the C and G meters respectively.

6. Press the red reset button on the lowest G decade.

7. Connect the component under test as shown in fig. 4.

8. Operate the decades as for normal measurements.

On the Low Impedance range the C polarity switch must be set to '-' for capacitance measurements, and to '+' for inductance measurements (i. e., opposite settings to those for normal measurements).

The G display is read directly in ohms. When measuring inductance on Range 1, the C polarity switch must be set to '+' and the figures of the C display, multiplied by 100, give inductance in microhenrys (unaffected by frequency). On Range 1 only, capacitance values (C polarity switch set to '-') are frequency dependent and the range multiplier (x 100μH) MUST NOT be used. Capacitance values are given by

$$\mu F = \frac{10^{10}}{\omega^2 C} \qquad \left[= \frac{100}{C} \text{ at } 1592\text{Hz} \right]$$

where C is the numerical value displayed.

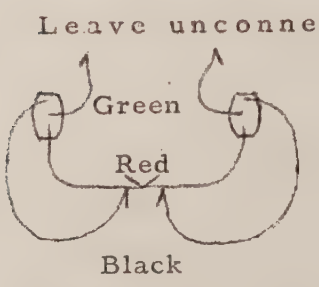

Fig. 3

Low Impedance Trimming Connections

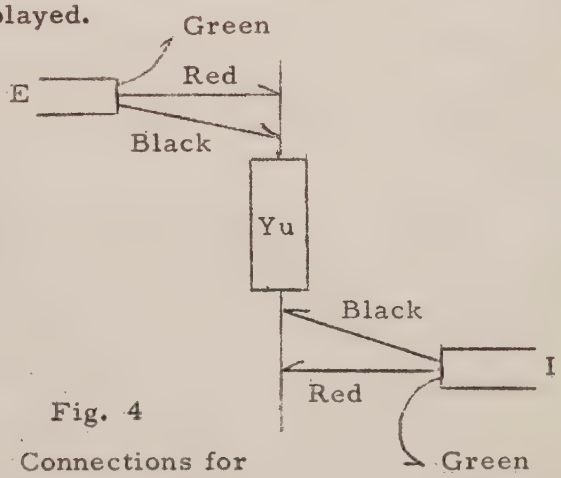

Fig. 4

Connections for Low Impedance Measurement

Vernier Controls

The C and G vernier controls have three functions:

(a) They permit a meter deflection to be off-set.

(b) Used to 'back-off' a meter reading to zero, they provide enhanced discrimination.

(c) When the Bridge is operated with an external source/detector, they are the fine balance controls.

Function (a) is particularly valuable for batch-testing of components and when a varying value is to be recorded. When the appropriate decades have been set the vernier control is used to adjust the meter deflection to any desired position - for example to mid-scale. The Autobalance facility will then give continuous readings (and the monitoring outputs) for changes in either sense. Also, the meter scale could be marked for acceptable upper and lower limits to meet a required component tolerance.

Function (b) arises because the inherent linearity of the potentiometer associated with the vernier is better than that normally obtainable from a moving-coil meter. The vernier reading taken when the meter deflection has been backed to zero, is about five times improved in resolution.

Function (c) arises because the Autobalance meter circuits are inoperative when an external source and detector are used. The operating procedure is given in the section 'External Source/Detector'.

The coverage provided by the Verniers is equivalent to the full-scale range of a meter when all three decades are in use. Because the meter sensitivity is reduced when only two decades, one decade, or no decades, are in use, the swing of the Verniers in these conditions is only about 10%, 1%, or 0.1% f. s. d. respectively.

Offset Windings

Two B. N. C. sockets (located behind the left-hand door) provide access to the E_{10} tap on the voltage transformer, and the I_{-12} tap on the current transformer. By connecting external standards to these points, a large part of any reading can be 'backed off', allowing the Bridge to be set to a

more sensitive range to provide increased discrimination. Further uses include the accurate comparison of two components (for example, an external standard in stabilized conditions could be compared with an 'unknown' subjected to various environmental conditions); components can be measured against external preset standards which could be switched in the form of a programme; also, on Range 5, two components can be compared, or matched, on a direct 1:1 basis.

The backing-off can be arranged to provide a discrimination 10 times better than on a normal measurement. This is extremely valuable for the plotting or observation of small variations. It must be appreciated, however, that the same order of discrimination is applied to the external standard component. For this reason it is usually necessary to use a component that is very stable and whose value is known precisely or is adjustable; the quality of the component must be sufficient to prevent its minor term from causing errors. This is particularly important when an external standard is being used to balance out the major term of an 'unknown' so as to allow a closer examination of its minor term.

The operation of the Bridge is described, firstly, as a comparator, secondly, for increased discrimination, and, finally, 'extension of trim controls'. All information on this facility applies equally to capacitance and conductance measurements. In principle, the use of the offset winding is equally applicable to inductance, but in this case signs must be changed and ratios must be inverted. To avoid confusion, it is preferable to consider inductance as a negative capacitance component and convert to actual inductance units only for the final results.

1. Comparator

The Bridge can be used for the direct comparison of components etc., by setting the Range switch to 5, this being the range having the same E and I turns product as the back windings. For this purpose, the 'unknown' should be connected in the normal way and the comparison component should be connected between the E_{10} and the I_{-12} sockets behind the left-hand door.

Before commencing the measurement, the Bridge should be trimmed in the usual way with all the zeros pressed and with all the leads connected to the appropriate sockets. The reset buttons should be engaged before the components are connected. The full sensitivity of the Bridge can then be achieved by engaging the decades (zeros or digits as appropriate) and the resulting indication, in conjunction with the Range 5 multiplier, will be the difference in value of the two components. If it proves necessary to turn one of the polarity switches to '-' to achieve a balance, this indicates that the component connected to the 'unknown' sockets has a smaller capacitance or conductance than that connected to the E_{10} and I_{-12} sockets. It is advisable to retrim the Bridge after changing polarity.

2. Increased Discrimination

The discrimination of the Bridge is improved by increasing the measurement range, but in so doing the balance of the 'unknown' goes outside the range of the internal standards. All or part of the unknown admittance must then be backed off by connecting an external admittance to the E_{10} and I_{-12} sockets. The procedure is then as follows:

(i) Measure the test component normally.

(ii) Determine a convenient amount to be backed off such that the portion remaining is within the scope of the next higher range (refer to the Table of Ranges in the Specification).

(iii) Select the next higher range, which gives a ten-times increase in discrimination.

(iv) The amount to be backed off, expressed as a multiple of the new range maximum multiplied by 10nF (or 100μ℧) is the value of the required backing-off component.

NOTE: The full-range value on any range is always equivalent to 10nF (or 100μ℧ or 10kΩ) on the offset winding.

Example

It is required to measure 650nF. This would normally be measured on Range 3, where the discrimination is 10pF. By selecting Range 4 and backing off 600nF, the measurement can be made with a discrimination of 1pF. The value of the backing-off capacitor required is determined

as follows.

Amount to be backed off (600nF) expressed as a multiple of the new range maximum (100nF on Range 4) gives a factor 6. Therefore the required value of backing-off capacitor is 6 x 10nF = 60nF. This should first be measured normally on Range 4 and then connected between the E_{10} and I_{-12} sockets. The test component is then measured as though its value were 50nF. The two measurements are then added together to give the required value.

3. Extension of Trim

It is sometimes necessary to trim out the effects of special clips, jigs, etc., or even an unwanted path that appears, effectively, across the test component. In cases where the coverage of the trim controls provided is inadequate or inconvenient, a suitably chosen component may be connected to the E_{10} and I_{-12} sockets. The required value is best obtained by measuring the shunt path on the Bridge and then connecting a component of appropriate value to the offset winding, exactly as described in the preceding sections.

EXTERNAL SOURCE AND DETECTOR

The B331 Autobalance circuits operate at a fixed angular frequency equal to 10^4 radians per second (1591.55Hz). When operation is essential at other frequencies, an external source and detector must be used. The illuminated numerals associated with the decades will still be operational but the two vernier controls must be used for the fine balance in place of the meters. The B. N. C. connectors for the external source and detector are fitted on the left-hand side panel. Above these is a switch which must be set as indicated to disconnect the internal source and detector and bring the external connectors into circuit.

Source

The impedance at the External Source socket of the B331 is approximately 15kΩ and the maximum permitted input is as follows:

between 400Hz and 10kHz - 100mV rms

below 400Hz - 250 x f mV rms (f in kHz)

between 10kHz and 20kHz - 50mV rms

NOTE: Below 200Hz the internal bridge trim control may be inadequate. If this is the case, extra trim can be obtained by using the Offset Windings as described under Extension of Trim (page 18).

Detector

With an input of 100mV rms at the External Source socket, the short-circuit current for 1% of the full-range capability (f. r. c.), that is, button 1 of the second decade operated, is as follows:

Capacitance - 22 x f nA rms (f in kHz)
Conductance - 35nA rms

The open-circuit voltage available in the 100 turn winding produced by this current is dependent upon the open-circuit impedance of the current transformer: the voltage level is best determined by actual measurement under the particular operating conditions.

Operation

All the operations described elsewhere will apply, but the Bridge should be re-trimmed whenever the frequency of operation is changed. The disposition of the leads during trimming and measurement, the use of low-capacity clips*, and allowance for the series inductance of the leads and the Bridge transformers must be taken into account when the External Source & Detector facility is used. These effects, which become increasingly important at the higher frequencies, arise because the Lead Eliminator system does not operate when an external source and detector are used.

When the source is first adjusted to the desired measurement frequency, and before the Bridge is balanced, the detector should be tuned to the point of maximum response. As balance is approached the tuning of the source (not the detector) may need adjustment.

Readout

Normal measurements of inductance are frequency-dependent, Also,

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* For example, Wayne Kerr Low-Capacity Leads Type LCC3.

measurements of capacitance (but not inductance) made on Range 1 are frequency-dependent.

Inductance (Ranges 2 to 8) is most easily derived by using the C multiplying factor for the range in use and then using the expression $L = 1/\omega^2 C$ where $\omega = 2\pi f$ and C is the value obtained after using the range multiplying factor. The units are basic (L in Henrys, C in Farads) and so 10^{-6} must be included if C is in μF, 10^{-9} for nF and 10^{-12} for pF. The expression can be written as

$$H = 1/(39.478 f^2 C) \qquad \text{(C in Farads)}$$

Capacitance on Range 1 is given by

$$\mu F = 10^{10}/(\omega^2 C)$$

where $\omega = 2\pi f$ and C is the numerical indication on the Bridge (decades plus vernier).

Accuracy

Bridge accuracy using the internal source and detector is 0.01% on C and G provided all decades are in use. Measurement of L is dependent on a precise knowledge of the Bridge frequency, which is accurate to ±100 p. p. m. The C and G accuracy obtainable at other frequencies is better than

±0.05%	200Hz - 10kHz
±0.075%	10kHz - 15kHz
±0.1%	15kHz - 20kHz

These figures apply also to L measurement where frequency is known accurately; otherwise allowance must be made (L values vary as $1/\text{frequency}^2$).

Low Impedance (Range 1) accuracy is given by adding 0.5% to the figures quoted above. In this case the figures apply to L and R. For C, measure frequency or make due allowance (C values vary as $1/\text{frequency}^2$).

To avoid errors arising from lead and contact resistance, Low Impedance (Range 1) measurements are made by connecting the Unknown as the shunt arm of a T-network. This technique gives a small inherent error* which, however, is known and can be allowed for by adding to the measured value a percentage derived as follows.

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* When the Bridge is used with its internal source and detector the lead eliminator automatically corrects this error.

Correction to be added = 0.2 x R_m where R_m is the measured value. 21
Example:

Measured value = 8Ω

Correction to be added = 0.2 x 8

= 1.6% which is the percentage by which R_m must be increased.

Therefore the true value $R = 8 + (\frac{1.6}{100} \times 8) = \underline{8.128\Omega}$

PARALLEL TO SERIES CONVERSION

Any impedance (or admittance) can be expressed in two ways:

(a) parallel components of the in-phase and quadrature terms

(b) series components of the in-phase and quadrature terms

Given values for the components in one form - (a) or (b) - values for the alternative form can be calculated to give an exact equivalent circuit at any one specified frequency of operation.

Because the Standards of the B331 Bridge are in parallel, the Unknown is measured in form (a). Expressions for obtaining the equivalent series components are given below. In the case of Low Impedance measurements, the bridge readings are in form (b).

$$R_s = 1/[G(1 + Q^2)]$$

$$C_s = C[1 + (1/Q^2)]$$

$$L_s = -1/[\omega^2 C(1 + 1/Q^2)] \qquad [Q = 2\pi fC/G]$$

$$X_s = X/[1 + (1/Q^2)]$$

where G and C are the values of the parallel components obtained from the bridge.

If $Q \gg 1$:

$$R_s \simeq 1/Q^2G \qquad C_s \simeq C \qquad L_s \simeq 1/(\omega^2 C) \qquad X_s \simeq X$$

If $Q \ll 1$:

$$R_s \simeq 1/G \qquad C_s \simeq X/Q^2 \qquad L_s \simeq Q^2/(\omega^2 C) \qquad X_s \simeq Q^2X$$

THREE- AND FOUR-TERMINAL OPERATION

When a component, such as a small-value capacitor, is mounted in a screening box, the Neutral connection from the Bridge should be connected to the box. One green lead should remain cross-connected (from E to I

or vice versa) and the second green lead provides the desired Neutral connection.

When four-terminal networks such as filters or attenuators are to be measured, the red and green leads from the E cable provide the input connections and the red and green leads from the I cable connect to the output terminals. In each case the green leads must be to the 'return' side of the network (a red-to-green 'crossover' must be avoided). The Kelvin clip cables can be used for these measurements, the green leads being used, as before, for the 'return' connections.

The neutral (green lead) of the E cable is connected, in the Bridge, to ground. The I neutral is floating.

MULTIPLES

10^{12}	Tera	T
10^{9}	Giga	G
10^{6}	Mega	M
10^{3}	Kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

APPENDIX - Lead Eliminator

A brief explanation of the principle of the lead eliminator will help the user to remember the method of connection. The basis of the measurement is that a known voltage E_u * drives a current I_u through the component under test Y_u.

The solution of the equation for the bridge at balance assumes that

$$I_u = E_u Y_u .$$

This is true only if the volt drop in the connecting leads is negligible compared with E_u. If the length of these leads is, say, two feet, a significant error is introduced on measurements below 500Ω or above 0.25μF. The lead eliminator senses the voltage actually across the unknown, E_{Yu} in fig.A, and compares this with a reference voltage E_R. The amount by which E_{Yu} falls short of E_R is added to E_u to restore the validity of the balance equation.

It will be appreciated, then, that it is essential that the lead eliminator connections are across the actual test component, i. e., level with, or inside the E and I connections as shown in fig.A. If the connections were not so made, E_{Yu} as sensed by the lead eliminator would include the volt drop at the E and I connection points.

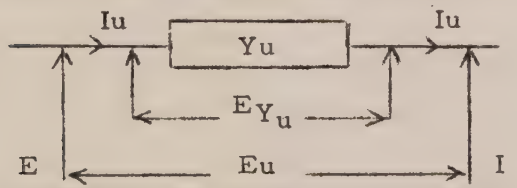

Fig. A
Lead Eliminator
Connections

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* The voltage actually applied to the unknown is given in the following table.

Range 8	15V
7	5V
6	1.5V
5	0.5V
4	150mV
3	50mV
2	15mV
1	Approx. 1.5mA

TABLE I

SPECIFICATION

MEASUREMENT RANGES

1 Basic (Parallel) Readings

CONDUCTANCE G (+ve or -ve)			Range	CAPACITANCE C		
1st. div.	Min for 0.01%	Max*(0.01%)		1st. div.	Min for 0.01%	Max*(0.01%)
1μMho	10mMho	100mMho	2	100pF	1μF	10μF
100nMho	1mMho	10mMho	3	10pF	0.1μF	1μF
10nMho	0.1mMho	1mMho	4	1pF	10nF	100nF
1nMho	10μMho	100μMho	5	100fF	1nF	10nF
100pMho	1μMho	10μMho	6	10fF	0.1nF	1nF
10pMho	0.1μMho	1μMho	7	1fF	10pF	100pF
1pMho	10nMho	100nMho	8	100aF	1pF	10pF

2 Derived Parallel Values

RESISTANCE R (+ve or -ve)			Range	INDUCTANCE L (1592Hz)‡		
Min. (0.01%)	Max for 0.01%	1st.div.		Min.(0.01%)	Max.for 0.01%	1st. div.
10Ω	100Ω	1MΩ	2	1mH	10mH	100H
100Ω	1kΩ	10MΩ	3	10mH	100mH	1kH
1kΩ	10kΩ	100MΩ	4	100mH	1H	10kH
10kΩ	100kΩ	1GΩ	5	1H	10H	100kH
100kΩ	1MΩ	10GΩ	6	10H	100H	1MH
1MΩ	10MΩ	100GΩ	7	100H	1kH	10MH
10MΩ	100MΩ	1TΩ	8	1kH	10kH	100MH

3 Low Impedance (Range 1) Series Values

Readout	Accuracy	R	L	C(1592)§
5 figures	0.2% ± 1 minor div.	1Ω - 10Ω	100μH - 1mH	10μF - 100μF
4 figures	0.3% ± 1 minor div.	100mΩ - 1Ω	10μH - 100μH	100μF - 1000μF
3 figures	1%	10mΩ - 100mΩ	1μH - 10μH	1mF - 10mF
Meter only	1% f. s. d.	100μΩ - 10mΩ	10nH - 1μH	10mF - 1 Farad

* Excluding overlap given with all decades at 10 (i. e. 11.11, etc.).
‡ Frequency-dependent: $L = 1/\omega^2 C$.
§ Frequency-dependent: $\mu F = 10^{10}/\omega^2 C$ (C is bridge <u>numerical</u> reading).

ACCURACY	±0.01% (see tables of Measurement Ranges)
DISCRIMINATION	G and C : 0.001% of Maximum (table 1) R and L : 0.001% of Minimum (table 2)
SOURCE FREQUENCY	Internal (normal production) : 1591.55Hz* ±0.01% " (to special order) : 1000.00Hz (Note: At 1000Hz, special procedures are necessary when measuring between 1-2.5mH and 10-25μF). External : 50Hz - 20kHz (for accuracies, see text on External Source/Detector).
OUTPUTS	0-100mV into ∤ 100kΩ, C and G (Other facilities to special order)
POWER REQUIREMENT	110/230V, 50/60Hz
DIMENSIONS	19 in. wide x 12 in. high x 9 in. deep (48.5 x 30.5 x 23 cm.)
WEIGHT	Approx. 50 lb. (22.3 kg.)

ANCILLARY ITEMS

Power Lead	D10879
Red Kelvin Lead	D15122
Blue Kelvin Lead	D15123
Red Low Impedance Lead	D15466
Blue Low Impedance Lead	D15467
Banana Plugs, Red (2 per inst.)	Belling & Lee L378/4/Red
Banana Plugs, Black (2 per inst.)	Belling & Lee L378/4/Black
Replacement Bulbs (Range Multiplier) (3 per inst.)	Ever Ready C.I.F. 21-6.3V/2W
Reciprocal Tables	D12461
Instrument Stand (Optional extra)	D12466

* Angular frequency $\omega = 2\pi f = 10^4$ radians/sec.

	0	1	2	3	4	5	6	7	8	9
1·0	1·00000	99010	98039	97087	96154	95238	94340	93458	92593	91743
1·1	90909	90090	89286	88496	87719	86957	86207	85470	84746	84034
1·2	83333	82645	81967	81301	80645	80000	79365	78740	78125	77519
1·3	76923	76336	75758	75188	74627	74074	73529	72993	72464	71942
1·4	71429	70922	70423	69930	69444	68966	68493	68027	67568	67114
1·5	66667	66225	65789	65359	64935	64516	64103	63694	63291	62893
1·6	62500	62112	61728	61350	60976	60606	60241	59880	59524	59172
1·7	58824	58480	58140	57803	57471	57143	56818	56497	56180	55866
1·8	55556	55249	54945	54645	54348	54054	53763	53476	53191	52910
1·9	52632	52356	52083	51813	51546	51282	51020	50761	50505	50251
2·0	50000	49751	49505	49261	49020	48780	48544	48309	48077	47847
2·1	47619	47393	47170	46948	46729	46512	46296	46083	45872	45662
2·2	45455	45249	45045	44843	44643	44444	44248	44053	43860	43668
2·3	43478	43290	43103	42918	42735	42553	42373	42194	42017	41841
2·4	41667	41494	41322	41152	40984	40816	40650	40486	40323	40161
2·5	40000	39841	39683	39526	39370	39216	39063	38911	38760	38610
2·6	38462	38314	38168	38023	37879	37736	37594	37453	37313	37175
2·7	37037	36900	36765	36630	36496	36364	36232	36101	35971	35842
2·8	35714	35587	35461	35336	35211	35088	34965	34843	34722	34602
2·9	34483	34364	34247	34130	34014	33898	33784	33670	33557	33445
3·0	33333	33223	33113	33003	32895	32787	32680	32573	32468	32362
3·1	32258	32154	32051	31949	31847	31746	31646	31546	31447	31348
3·2	31250	31153	31056	30960	30864	30769	30675	30581	30488	30395
3·3	30303	30211	30120	30030	29940	29851	29762	29674	29586	29499
3·4	29412	29326	29240	29155	29070	28986	28902	28818	28736	28653
3·5	28571	28490	28409	28329	28249	28169	28090	28011	27933	27855
3·6	27778	27701	27624	27548	27473	27397	27322	27248	27174	27100
3·7	27027	26954	26882	26810	26738	26667	26596	26525	26455	26385
3·8	26316	26247	26178	26110	26042	25974	25907	25840	25773	25707
3·9	25641	25575	25510	25445	25381	25316	25253	25189	25126	25063
4·0	25000	24938	24876	24814	24752	24691	24631	24570	24510	24450
4·1	24390	24331	24272	24213	24155	24096	24038	23981	23923	23866
4·2	23810	23753	23697	23641	23585	23529	23474	23419	23364	23310
4·3	23256	23202	23148	23095	23041	22989	22936	22883	22831	22779
4·4	22727	22676	22624	22573	22523	22472	22422	22371	22321	22272
4·5	22222	22173	22124	22075	22026	21978	21930	21882	21834	21786
4·6	21739	21692	21645	21598	21552	21505	21459	21413	21368	21322
4·7	21277	21231	21186	21142	21097	21053	21008	20964	20921	20877
4·8	20833	20790	20747	20704	20661	20619	20576	20534	20492	20450
4·9	20408	20367	20325	20284	20243	20202	20161	20121	20080	20040
5·0	20000	19960	19920	19881	19841	19802	19763	19724	19685	19646
5·1	19608	19569	19531	19493	19455	19417	19380	19342	19305	19268
5·2	19231	19194	19157	19120	19084	19048	19011	18975	18939	18904
5·3	18868	18832	18797	18762	18727	18692	18657	18622	18587	18553
5·4	18519	18484	18450	18416	18382	18349	18315	18282	18248	18215
	0	1	2	3	4	5	6	7	8	9

PROPORTIONAL PARTS OF MEAN DIFFERENCES

	1	2	3	4	5	6	7	8	9
1·0									
1·1									
1·2									
1·3									
1·4									
1·5	42	83	125	167	209	250	292	334	375
1·6	37	74	110	147	184	221	258	294	331
1·7	33	65	98	131	164	196	229	262	294
1·8	29	58	88	117	146	175	204	234	263
1·9	26	53	79	105	132	158	184	210	237
2·0	24	48	71	95	119	143	167	190	214
2·1	22	43	65	86	108	130	151	173	194
2·2	20	40	59	79	99	119	139	158	178
2·3	18	36	54	72	91	109	127	145	163
2·4	17	33	50	67	84	100	117	134	150
2·5	15	31	46	62	77	92	108	123	139
2·6	14	29	43	57	72	86	100	114	129
2·7	13	26	40	53	66	79	92	106	119
2·8	12	25	37	49	62	74	86	98	111
2·9	12	23	35	46	58	69	81	92	104
3·0	11	22	32	43	54	65	76	86	97
3·1	10	20	30	40	51	61	71	81	91
3·2	10	19	29	38	48	57	67	76	86
3·3	9	18	27	36	45	53	62	71	80
3·4	8	17	25	34	42	50	59	67	76
3·5	8	16	24	32	40	47	55	63	71
3·6	8	15	23	30	38	45	53	60	68
3·7	7	14	21	28	36	43	50	57	64
3·8	7	14	20	27	34	41	48	54	61
3·9	6	13	19	26	32	38	45	51	58
4·0	6	12	18	24	31	37	43	49	55
4·1	6	12	17	23	29	35	41	46	52
4·2	6	11	17	22	28	33	39	44	50
4·3	5	11	16	21	27	32	37	42	48
4·4	5	10	15	20	26	31	36	41	46
4·5	5	10	14	19	24	29	34	38	43
4·6	5	9	14	18	23	28	32	37	41
4·7	4	9	13	18	22	26	31	35	40
4·8	4	9	13	17	22	26	30	34	39
4·9	4	8	12	16	20	25	29	33	37
5·0	4	8	12	16	20	24	27	31	35
5·1	4	8	11	15	19	23	26	30	34
5·2	4	7	11	15	18	22	25	29	33
5·3	3	7	10	14	18	21	24	28	31
5·4	3	7	10	14	17	20	24	27	30
	1	2	3	4	5	6	7	8	9

	0	1	2	3	4	5	6	7	8	9
5·5	18182	18149	18116	18083	18051	18018	17986	17953	17921	17889
5·6	17857	17825	17794	17762	17731	17699	17668	17637	17606	17575
5·7	17544	17513	17483	17452	17422	17391	17361	17331	17301	17271
5·8	17241	17212	17182	17153	17123	17094	17065	17036	17007	16978
5·9	16949	16920	16892	16863	16835	16807	16779	16750	16722	16694
6·0	16667	16639	16611	16584	16556	16529	16502	16474	16447	16420
6·1	16393	16367	16340	16313	16287	16260	16234	16207	16181	16155
6·2	16129	16103	16077	16051	16026	16000	15974	15949	15924	15898
6·3	15873	15848	15823	15798	15773	15748	15723	15699	15674	15649
6·4	15625	15601	15576	15552	15528	15504	15480	15456	15432	15408
6·5	15385	15361	15337	15314	15291	15267	15244	15221	15198	15175
6·6	15152	15129	15106	15083	15060	15038	15015	14993	14970	14948
6·7	14925	14903	14881	14859	14837	14815	14793	14771	14749	14728
6·8	14706	14684	14663	14641	14620	14599	14577	14556	14535	14514
6·9	14493	14472	14451	14430	14409	14388	14368	14347	14327	14306
7·0	14286	14265	14245	14225	14205	14184	14164	14144	14124	14104
7·1	14085	14065	14045	14025	14006	13986	13966	13947	13928	13908
7·2	13889	13870	13850	13831	13812	13793	13774	13755	13736	13717
7·3	13699	13680	13661	13643	13624	13605	13587	13569	13550	13532
7·4	13514	13495	13477	13459	13441	13423	13405	13387	13369	13351
7·5	13333	13316	13298	13280	13263	13245	13228	13210	13193	13175
7·6	13158	13141	13123	13106	13089	13072	13055	13038	13021	13004
7·7	12987	12970	12953	12937	12920	12903	12887	12870	12853	12837
7·8	12821	12804	12788	12771	12755	12739	12723	12706	12690	12674
7·9	12658	12642	12626	12610	12594	12579	12563	12547	12531	12516
8·0	12500	12484	12469	12453	12438	12422	12407	12392	12376	12361
8·1	12346	12330	12315	12300	12285	12270	12255	12240	12225	12210
8·2	12195	12180	12165	12151	12136	12121	12107	12092	12077	12063
8·3	12048	12034	12019	12005	11990	11976	11962	11947	11933	11919
8·4	11905	11891	11876	11862	11848	11834	11820	11806	11792	11779
8·5	11765	11751	11737	11723	11710	11696	11682	11669	11655	11641
8·6	11628	11614	11601	11587	11574	11561	11547	11534	11521	11507
8·7	11494	11481	11468	11455	11442	11429	11416	11403	11390	11377
8·8	11364	11351	11338	11325	11312	11299	11287	11274	11261	11249
8·9	11236	11223	11211	11198	11186	11173	11161	11148	11136	11123
9·0	11111	11099	11086	11074	11062	11050	11038	11025	11013	11001
9·1	10989	10977	10965	10953	10941	10929	10917	10905	10893	10881
9·2	10870	10858	10846	10834	10823	10811	10799	10787	10776	10764
9·3	10753	10741	10730	10718	10707	10695	10684	10672	10661	10650
9·4	10638	10627	10616	10604	10593	10582	10571	10560	10549	10537
9·5	10526	10515	10504	10493	10482	10471	10460	10449	10438	10428
9·6	10417	10406	10395	10384	10373	10363	10352	10341	10331	10320
9·7	10309	10299	10288	10277	10267	10256	10246	10235	10225	10215
9·8	10204	10194	10183	10173	10163	10152	10142	10132	10121	10111
9·9	10101	10091	10081	10070	10060	10050	10040	10030	10020	10010
	0	1	2	3	4	5	6	7	8	9

	1	2	3	4	5	6	7	8	9
5·5	3	7	10	13	16	20	23	26	29
5·6	3	6	9	13	16	19	22	25	28
5·7	3	6	9	12	15	18	21	24	27
5·8	3	6	9	12	15	18	20	23	26
5·9	3	6	9	11	14	17	20	23	25
6·0	3	6	8	11	14	16	19	22	25
6·1	3	5	8	11	13	16	19	21	24
6·2	3	5	8	10	13	15	18	21	23
6·3	2	5	7	10	12	15	17	20	22
6·4	2	5	7	10	12	14	17	19	22
6·5	2	5	7	9	12	14	16	19	21
6·6	2	5	7	9	11	14	16	18	20
6·7	2	4	7	9	11	13	15	18	20
6·8	2	4	6	9	11	13	15	17	19
6·9	2	4	6	8	10	12	14	17	19
7·0	2	4	6	8	10	12	14	16	18
7·1	2	4	6	8	10	12	14	16	18
7·2	2	4	6	8	10	11	13	15	17
7·3	2	4	6	7	9	11	13	15	17
7·4	2	4	5	7	9	11	13	15	16
7·5	2	4	5	7	9	11	12	14	16
7·6	2	3	5	7	9	10	12	14	15
7·7	2	3	5	7	8	10	12	13	15
7·8	2	3	5	7	8	10	11	13	15
7·9	2	3	5	6	8	9	11	13	14
8·0	2	3	5	6	8	9	11	12	14
8·1	2	3	5	6	8	9	11	12	14
8·2	1	3	4	6	7	9	10	12	13
8·3	1	3	4	6	7	9	10	11	13
8·4	1	3	4	6	7	8	10	11	13
8·5	1	3	4	5	7	8	10	11	12
8·6	1	3	4	5	7	8	9	11	12
8·7	1	3	4	5	7	8	9	10	12
8·8	1	3	4	5	6	8	9	10	12
8·9	1	3	4	5	6	8	9	10	11
9·0	1	2	4	5	6	7	9	10	11
9·1	1	2	4	5	6	7	8	10	11
9·2	1	2	4	5	6	7	8	9	11
9·3	1	2	4	5	6	7	8	9	10
9·4	1	2	3	4	6	7	8	9	10
9·5	1	2	3	4	5	7	8	9	10
9·6	1	2	3	4	5	6	8	9	10
9·7	1	2	3	4	5	6	7	8	10
9·8	1	2	3	4	5	6	7	8	9
9·9	1	2	3	4	5	6	7	8	9
	1	2	3	4	5	6	7	8	9

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